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(54) DYNAMIC IMPEDANCE MATCHING NETWORKS

(75) Inventor: Eugene Wilson, Culver City, CA (US)

(73) Assignee: Xerox Corporation, Stamford, CT (US)

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(51) Int. Cl.[7] B41J 2/01
(52) U.S. Cl. 347/9; 347/12
(58) Field of Search 347/9, 10, 19, 347/46, 12, 40

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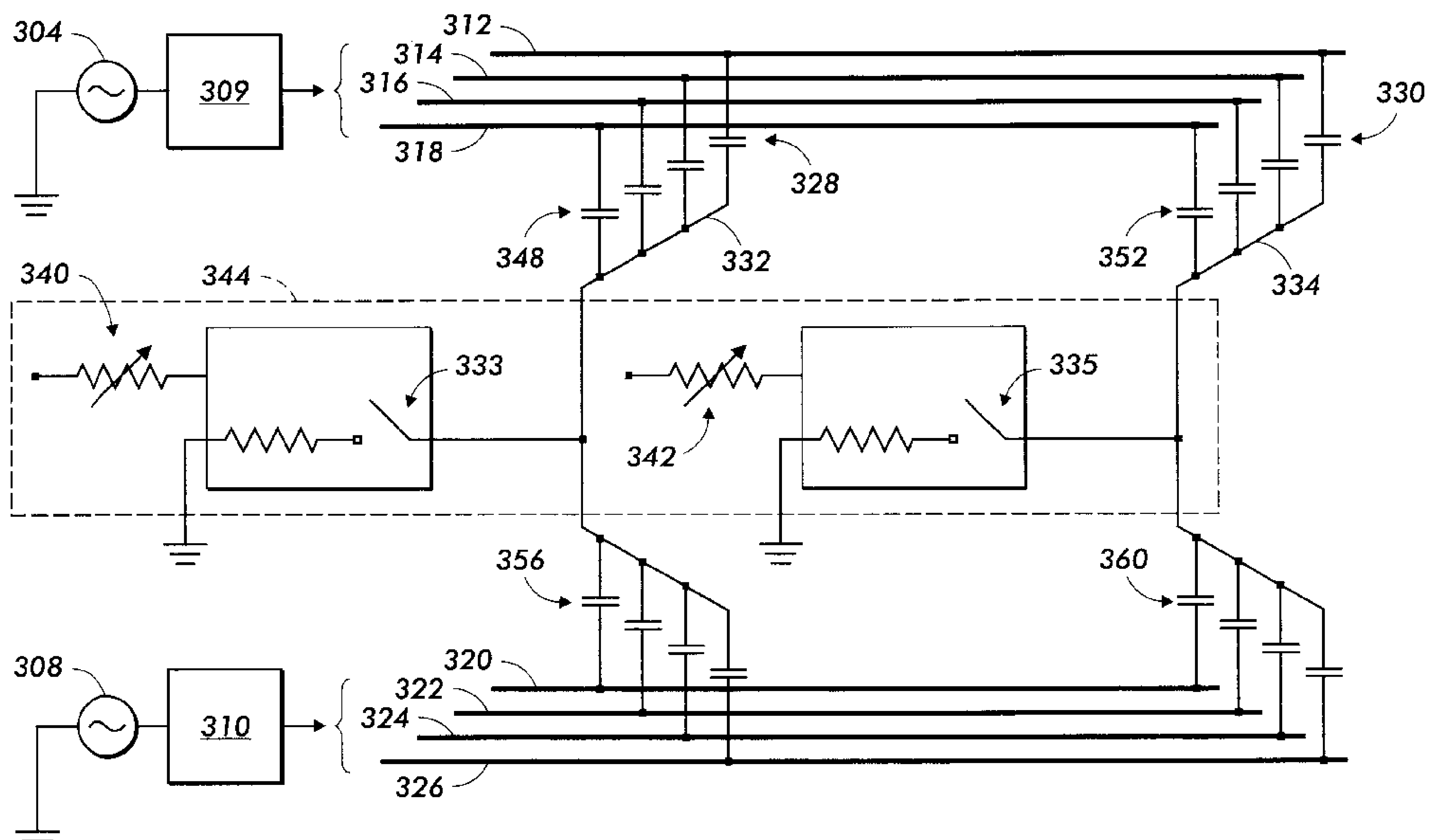
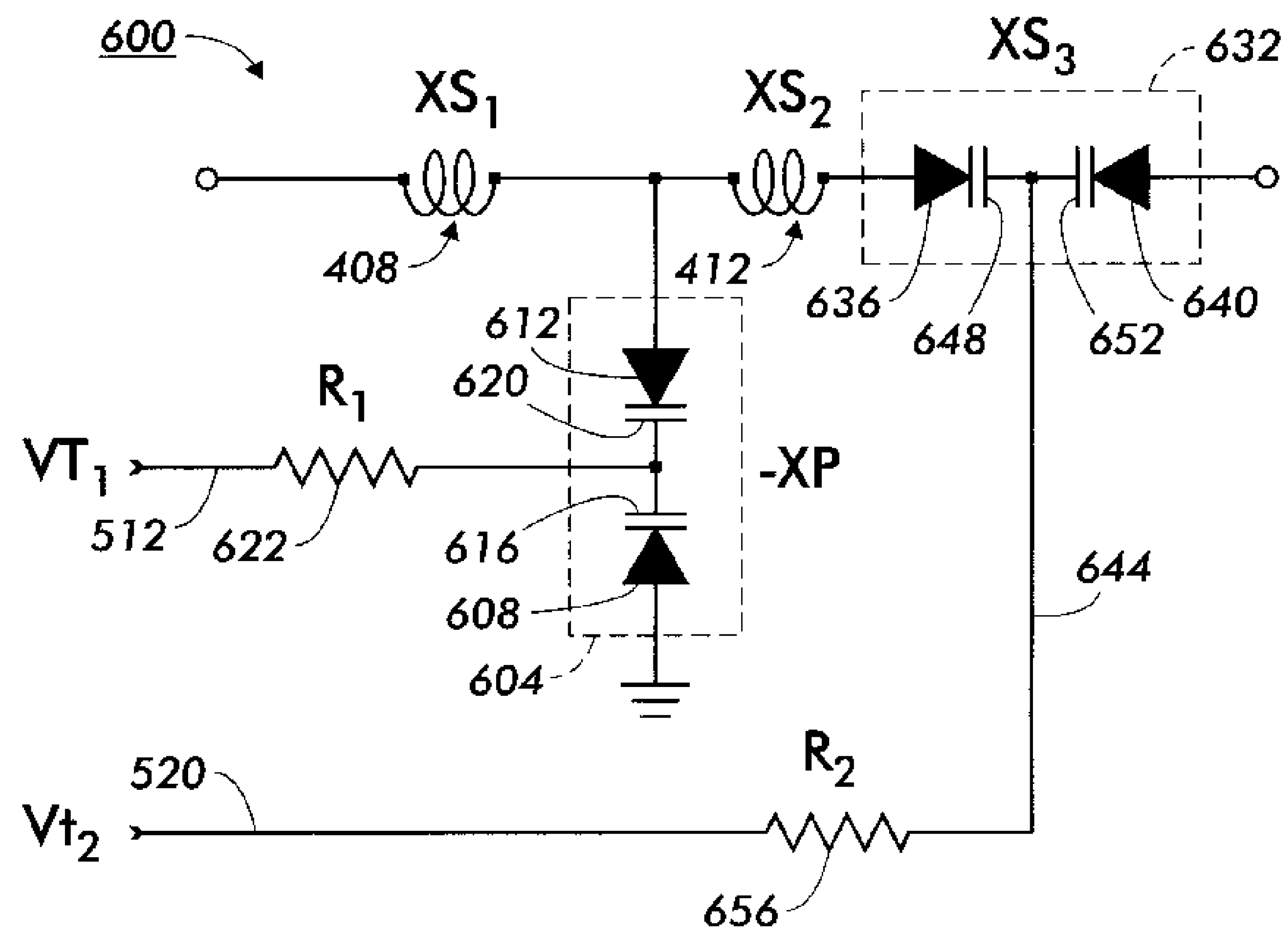
Primary Examiner—Craig Hallacher
(74) Attorney, Agent, or Firm—Kent Chen

(57) ABSTRACT

An improved matching networks for matching the impedance of a source of variable frequency oscillating energy to a variable load is described. The described matching network includes variable capacitances that can be changed to maintain an impedance match between a source and a load despite rapid changes in the frequency output by the source and rapid changes in load impedance.

17 Claims, 5 Drawing Sheets





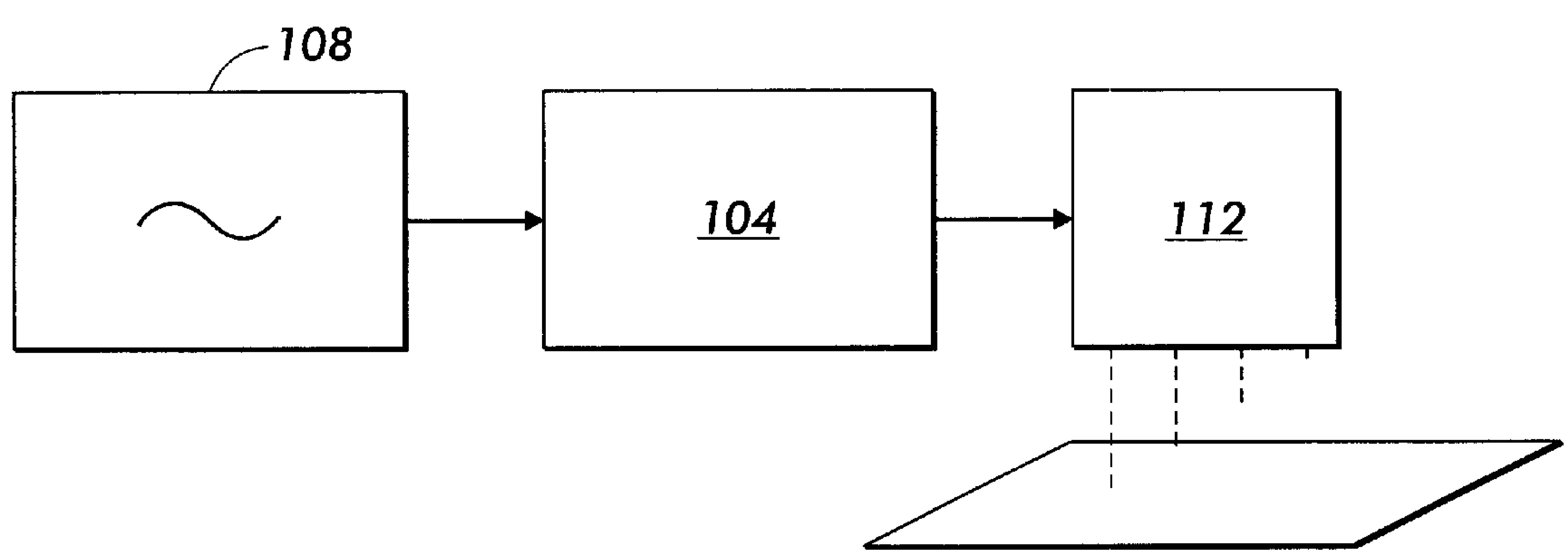


FIG. 1

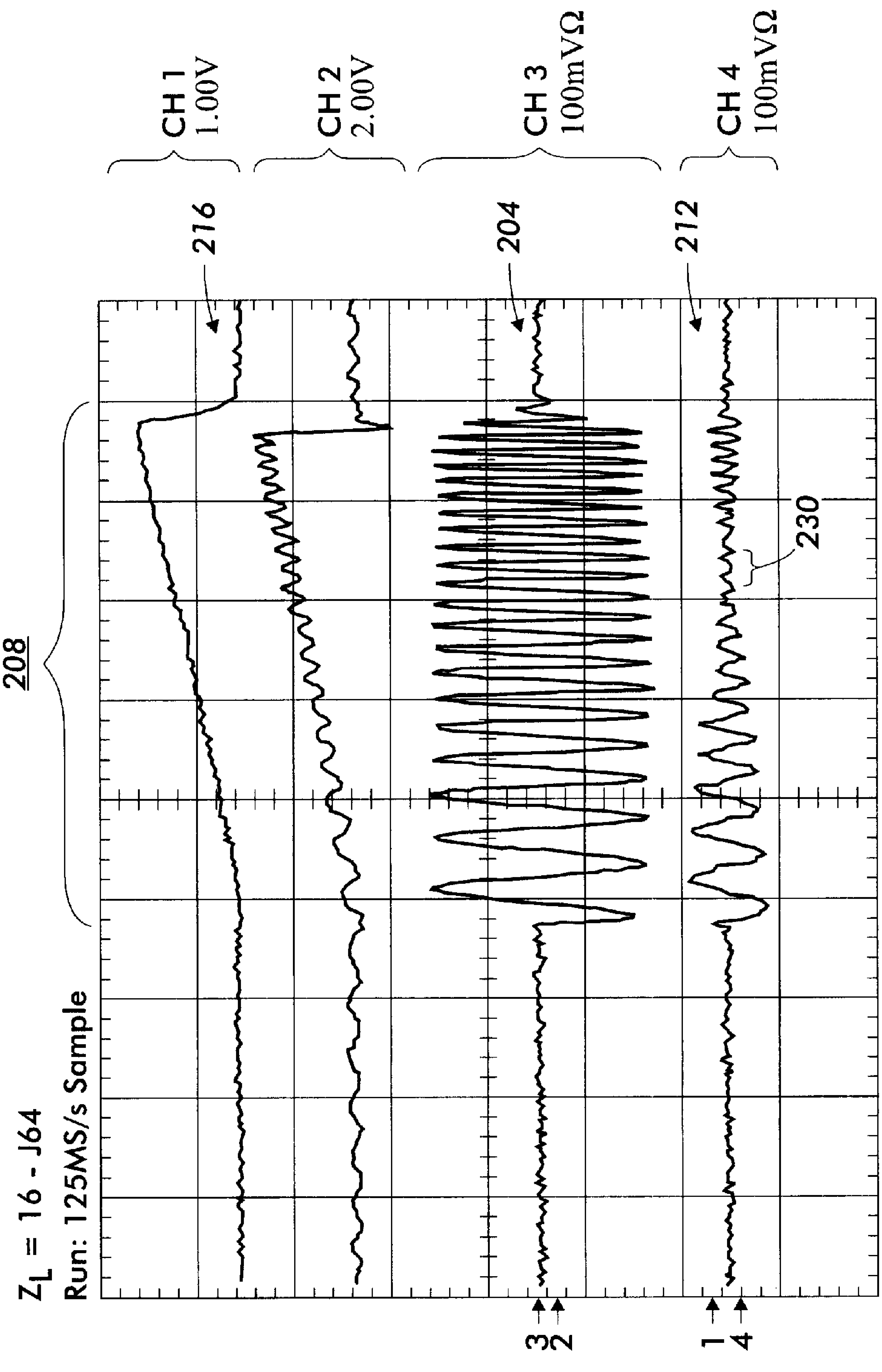
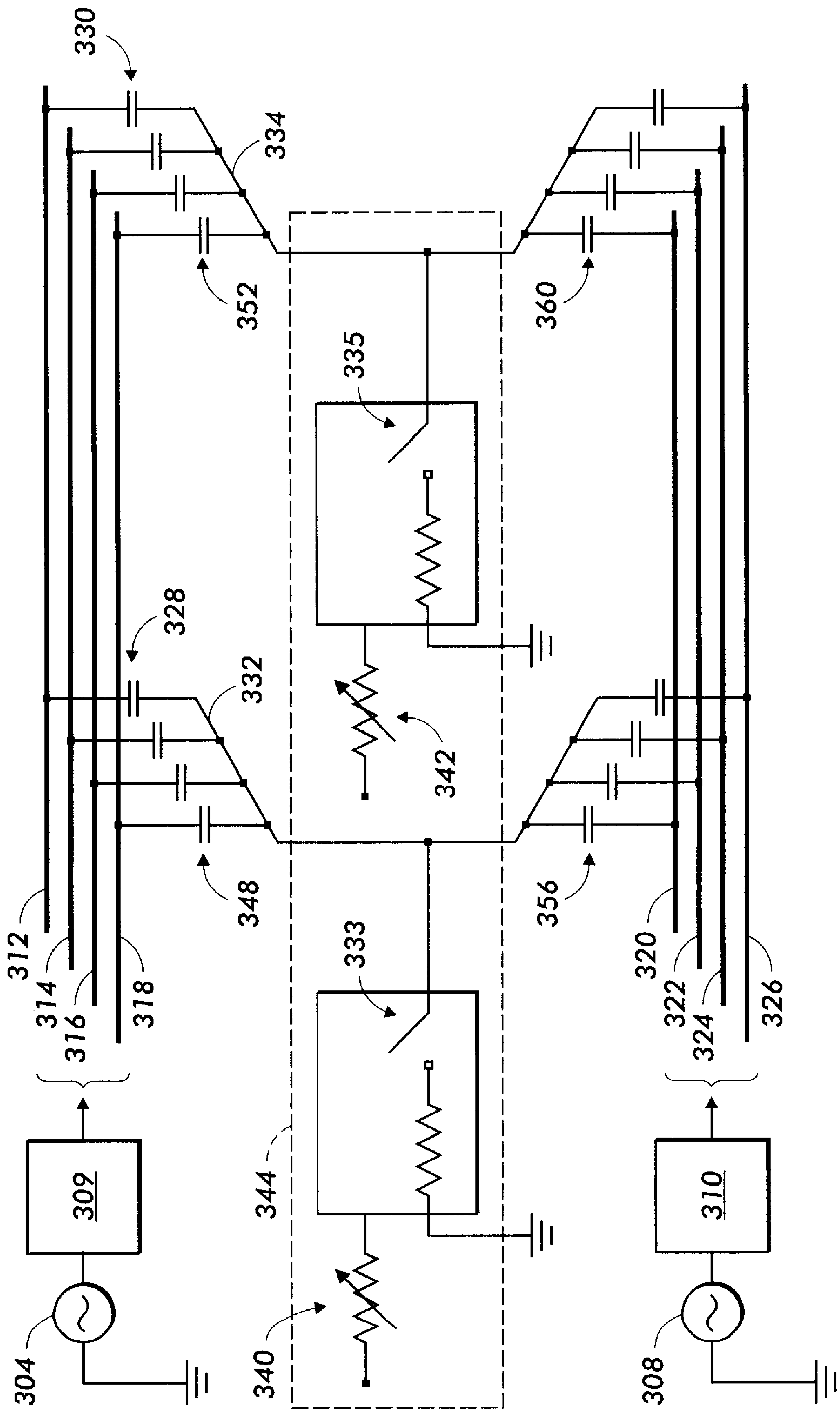

CH 1
1.00V
CH 2
2.00V
CH 3
100mVΩ
CH 4
100mVΩ
216
204
212
208
230
Z_L = 16 - J64
Run: 125MS/s Sample
3
2
1
4

FIG. 2


330
334
352
360
335
328
332
342
348
356
333
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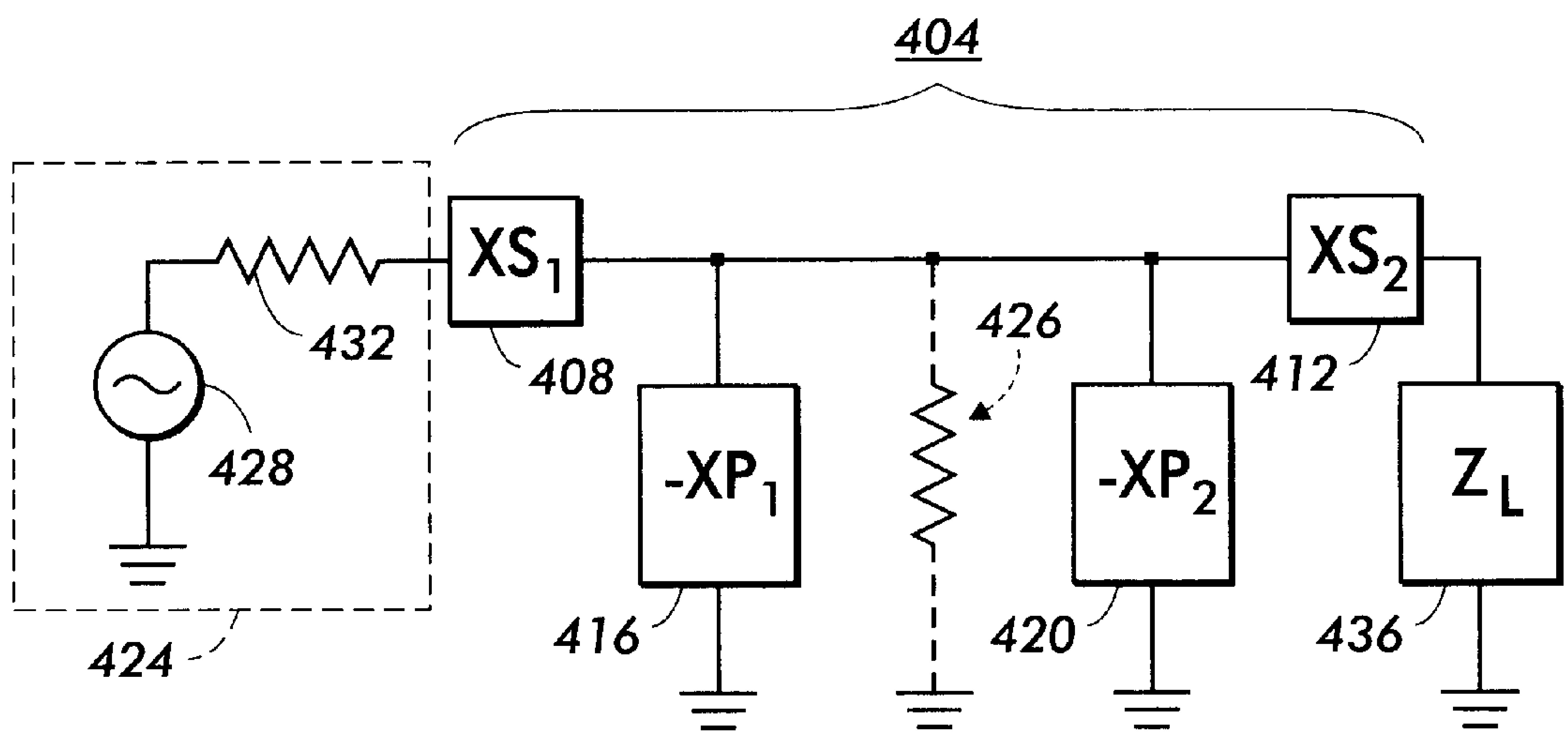
318
320
322
324
326
309
310
344
340
304
308

FIG. 3

FIG. 4


404
XS1
432
408
428
424
-XP1
416
426
-XP2
420
XS2
412
ZL
436

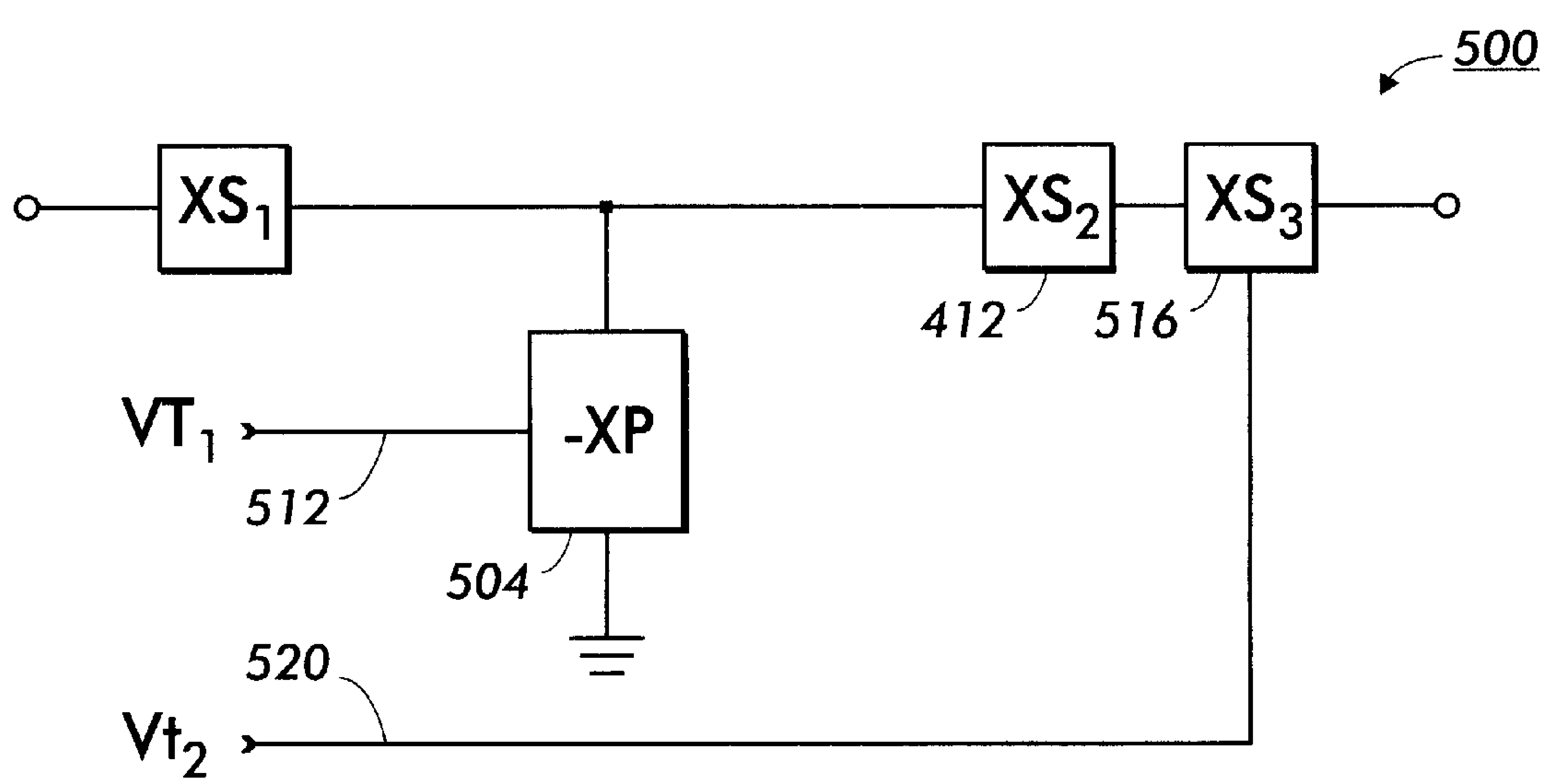

500
XS1
XS2
XS3
412
516
VT1
512
-XP
504
520
Vt2

FIG. 5

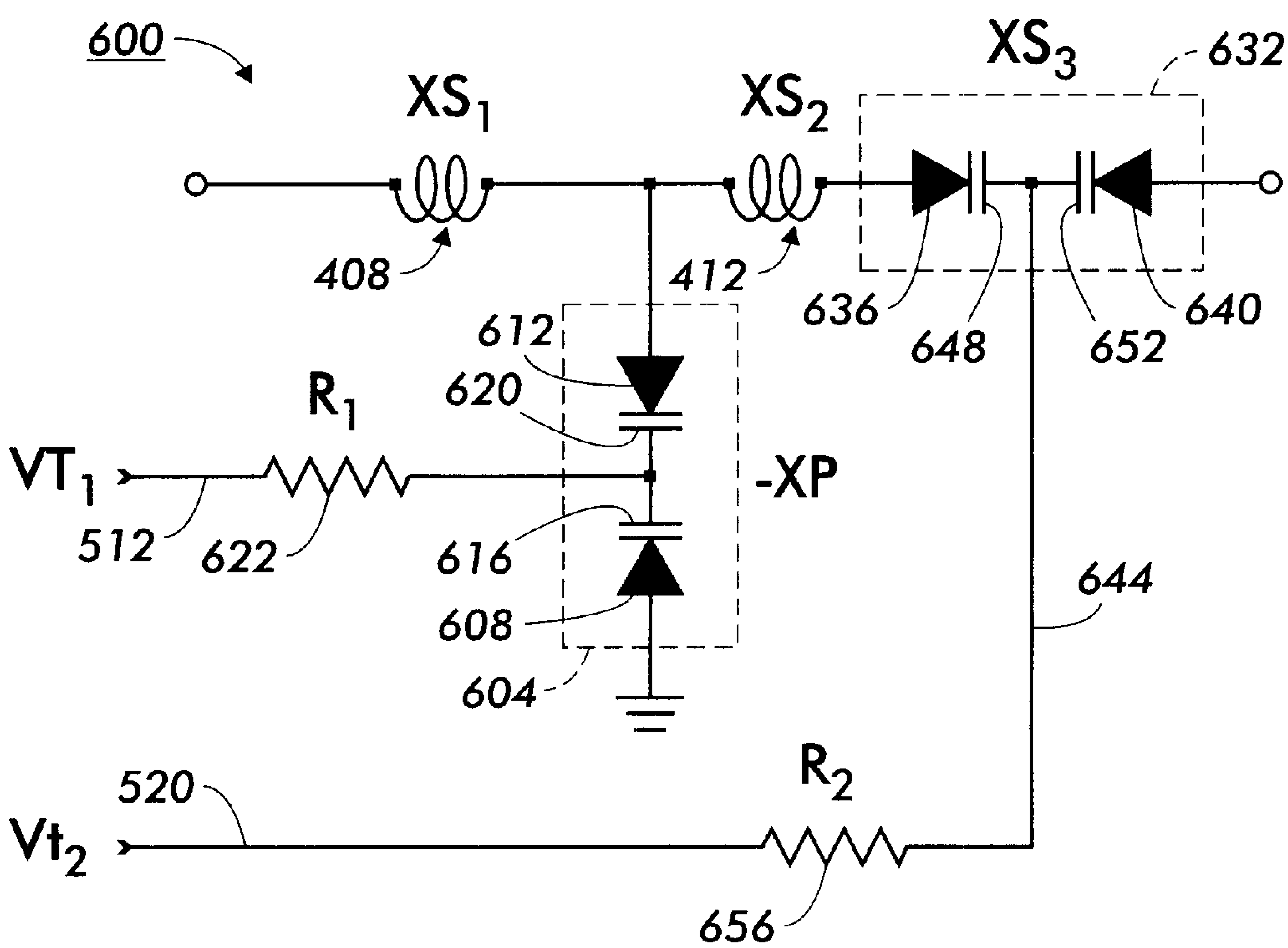

600
XS1
XS2
XS3
632
408
412
636
648
652
640
612
620
R1
VT1
-XP
512
622
616
608
604
644
R2
520
Vt2
656

FIG. 6

DYNAMIC IMPEDANCE MATCHING NETWORKS

BACKGROUND

Acoustic Ink Printers (AIP), utilize acoustic waves to drive ink droplets from an AIP Print head. Acoustic waves generate droplets that are smaller and more precisely directed then current ink jet printers. A description of AIP printers is provided in U.S. patent application Ser. No. 09/363,593 entitled Method and Apparatus to Provide Adjustable Excitement of a Transducer in a Printing System in Order to Compensate for Different Transducer Efficiencies, filed Jul. 29, 1999, assigned to Xerox Corporation and hereby incorporated by reference.

In order to provide oscillating energy for an AIP printhead, a RF source is typically coupled to the AIP printhead. Optimal transfer of power from the RF source to the AIP printhead occurs when the output impedance of the RF source matches the input impedance of a load. In an AIP system, the load is an AIP printhead. However, in typical AIP systems, several factors make it difficult to match the source and load impedance.

A first factor that makes it difficult to match impedances is the changing frequency output of the RF source. In AIP systems, the frequency of the RF source output continuously changes over a predetermined frequency range to prevent the formation of standing waves and resonant effects within the AIP printhead. Unfortunately, changing the frequency of the RF source also makes it difficult to create an impedance match between the RF source and the AIP printhead because the impedance of the AIP printhead is a function of frequency. Changing frequencies result in a varying reactive component of impedance that makes it difficult to maintain an impedance match.

A second complication that makes it difficult to create an impedance match arises from the changing number of ejectors being fired. A typical AIP printhead includes a plurality of ejectors distributed across the printhead. The number of ejectors fired changes with the density of ink needed on an image. For example, when printing a dark image, multiple ejectors may be fired simultaneously to darken a region of a drawing. When printing a "light" image, one or even no ejectors may be fired for extended periods of time. Each ejector is associated with an impedance. Thus, changing the number of ejectors fired changes the overall impedance of the printhead.

Due to the previously described difficulties, most current acoustic ink printing systems do not match impedances. Instead, current systems compensate for power losses by using higher powered RF sources that provide larger amounts of power. However, such systems are inefficient and consume significant amounts of power. The wasted power generates heat that must be removed.

Thus an improved method and apparatus to transfer power from a variable frequency source such as a RF source to a variable load such as an AIP printhead is needed.

SUMMARY OF THE INVENTION

An improved matching network for matching the impedance of a source of variable frequency oscillating energy to a variable load is described. The described matching network includes a first reactive element that adjusts a first capacitance according to the frequency of the received oscillating energy. The matching network also includes a second reactive element that adjusts a second capacitance according to the impedance of a load. By adjusting the impedances of the two reactive elements, an approximate impedance match between the variable frequency oscillating energy source and the variable load is achieved. The described matching network is particularly suitable for use in acoustic ink printing systems, although the matching network is also useful in other systems, and the invention should not be limited to acoustic ink printing systems.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram that shows the use of an impedance matching network between a RF source and a printhead.

FIG. **2** are example plots illustrating the signals processed and output by a sample impedance matching network.

FIG. **3** illustrates a switching circuit in a typical AIP printhead load.

FIG. **4** illustrates a matching network that utilizes back to back "L"s to form an impedance matching network.

FIG. **5** illustrates the impedance matching network of FIG. **4** in which the shunt impedances are summed and both a shunt impedance and a series impedance are made variable.

FIG. **6** illustrates one embodiment of the invention in which tuning diodes are used to achieve variable reactive elements that serve respectively as a variable shunt impedance and a variable series impedance for the matching is network.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** illustrates an impedance matching network **104** that transfers output from a RF source **108** to a load such as a printhead **112**. When used for AIP printing applications, the RF source typically outputs a driver signal that ranges in frequency between 135 and 155 Megahertz (MHz), although other frequency ranges are possible.

In FIG. **2**, plot line **204** represents one example of a driver signal output by RF source **108** of FIG. **1**. The driver signal provides energy to ink ejectors on AIP printhead **112**. In the driver signal illustrated by plot line **204**, the frequency of the driver signal increases approximately linearly, from 135 MHz to 155 MHz, over each cycle such as period **208**.

FIG. **3** illustrates one example of a switching architecture in an AIP printhead that serves as part of load **112** of FIG. **1**. In FIG. **3**, the illustrated switching architecture receives driver signals from a RF energy source and a matching network and redirects the signal to a plurality of transducers. Each transducer provides acoustic energy for a corresponding droplet source. In the illustrated embodiment, two RF sources **304**, **308** provide RF energy through respective matching networks **309**, **310** and then along row lines **312**, **314**, **316**, **318**, **320**, **322**, **324**, **326**. Each row line, such as row line **312**, is coupled to one or more corresponding transducers, such as transducers **328**, **330**. The output of transducers **328**, **330** are controlled by the signal along row line **312** and the signal transmitted along columns **332**, **334**. Only when RF source **304** provides a RF signal along row line **312** and an appropriate input is transmitted along column **332** does transducer **328** receive sufficient energy to output a droplet. In one embodiment of the invention, the "signal" along columns **332**, **334** is determined by the setting of "three-terminal" switches **333**, **335**. When switch **333** is closed, column **332** is coupled to ground. When switch **333** is open, column **332** is left electrically floating. In one embodiment of the invention, each of the switches may be implemented as a "three-terminal switch" as described in U.S. Pat. No. 5,757,065 issued to Buhler, et al. and hereby incorporated by reference. By synchronizing the timing of the RF signal along row lines with the timing of the switches, the output of transducers **328, 330** can be independently controlled. In the illustrated embodiment, the timing of the switches is controlled by the timing of the injector current in each switch.

In one embodiment of the invention, resistors **340, 342** are variable resistors, typically metal oxide semiconductors (MOS) transistors. The resistance of resistors **340, 342** controls the amount of current flowing from the transducers and along columns **332, 334**. In one embodiment of the invention, switches **333, 335** and variable resistors **340, 342** may be implemented as a network on a chip **344** that forms part of the circuitry of a print head driver. As used herein, a print head driver is any circuit that controls the energy delivered to the transducer.

Typically, a switch supplies one of two discrete impedances (typically a "hi" value and a "low" value) to columns **332, 334**. A change in the applied impedance changes the amount of current flowing through each transducer to either cause or prevent ejection of a droplet from a droplet source coupled to the transducer. To compensate for the different positions of the transducer with respect to the RF source, as well as to compensate for differences among transducers resulting from variations during the transducer manufacturing process, the resistance of resistors **340, 342** may be adjusted to one of several values to compensate for the line losses which occur. Resistors **340, 342** are set to cause RF source **304** to deliver approximately equal amounts of power to transducer **328** and transducer **330**.

As previously described and illustrated in FIG. **3**, the setting of resistors **340, 342**, as well as the number of capacitors from capacitors **348, 352, 356, 360** coupled to the RF source changes in response to which ejectors are fired and the number of ejectors fired at any particular point in time. In particular, the firing of additional ejectors at a particular moment in time increases the load capacitance.

Returning to FIG. **1**, impedance matching network **104** maintains an approximate impedance match between RF source **108** and load **112** despite changing driver frequencies and load impedances. In one implementation of impedance matching network **104**, RF source **108** generates a frequency indicator signal with a voltage proportional to the frequency of the drive signal. RF source **108** transmits the frequency indicator signal to impedance matching network **104**. Plot line **216** of FIG. **2** illustrates a typical frequency indicator signal that corresponds to the drive signal of plot line **204**. One embodiment of an impedence matching network that uses the frequency indicator signal of plot line **216** will be described in FIG. **6**. In some commercially available RF generators, the frequency indicator signal can be obtained from a scaled output of the ramp generator of the RF generator.

When used to transfer drive signals for an AIP printer, the impedance matching network uses print information from the print signal to determine load impedance. The print signal is processed to determine how many acoustic ink ejectors are being fired. Changing the number of ink ejectors being fired changes the input impedance of the AIP printhead. FIGS. **4–6** and the accompanying discussion describe an impedance matching network that adjusts capacitances of impedance elements in the impedance matching network to correspond to changing load conditions and thereby minimize the reflected power.

FIG. **4** illustrates a "L" impedance matching network **404** including a first series impedance **408**, a second series impedance **412**, a first shunt impedance **416** and a second shunt impedance **420**. The first series impedance **408** and the first shunt impedance **416** form a first "L" network that matches the output impedance **432** of a source **424** to a virtual resistor **426**. The resistance of the virtual resistor is substantially larger than source output impedance **432**. Likewise, the second series impedance **412** and the second shunt impedance **420** form a second "L" network that matches the load impedance **436** to virtual resistor **426**. The resistance of virtual resistor **426** is also substantially larger than load impedance **436**.

In FIG. **4**, RF source **424** includes a voltage generator **428** and a source output impedance **432**. A typical value for source output impedance **432** is 50 Ohms. Thus virtual resistor **426** will be substantially larger than 50 Ohms. When load impedance **436** is an AIP printhead, the value of load impedance **436** will typically vary from 4-j16 to 16-j64 Ohms for frequencies between 135 MHz and 155 MHz.

The "L" impedance circuit of FIG. **4** can be simplified by combining first shunt impedance **416** and second shunt impedance **420** into a combination shunt impedance **504** of FIG. **5** to form a "T" impedance circuit. The impedance of combined shunt impedance **504** is approximately equal to the sum of shunt impedance **416** and shunt impedance **420**. The design of "L" impedance networks and subsequent conversions to the "T" impedance network of FIG. **5** are described on page 73–75 of the book "RF Circuit Design" by Chris Bowick, published in 1982, sixth printing 1988 and hereby incorporated by reference.

Creating a combined shunt impedance **504** does not solve the problem of changes in impedance of fixed reactive elements (inductors and capacitors) in matching network **500**. Each fixed reactive element in matching network **500** changes impedance when the frequency of a drive signal from voltage generator **428** changes. To compensate for changes in frequency, the capacitance or inductance of reactive elements in combined shunt impedance **504** are made variable.

In order to control the inductance and capacitance of reactive elements in shunt impedance **504**, frequency indicator line **512** carries a frequency control signal to shunt impedance **504**. The frequency control signal communicates the frequency of the drive signal output by the RF source. In one embodiment, the voltage of the frequency control signal is proportional to the frequency of the drive signal. The matching network uses the voltage of the frequency control signal to adjust the impedance of variable reactive elements in shunt impedance **504**. One method of implementing a variable shunt impedance **504** that can rapidly respond to changes in frequency of a drive signal will be described in FIG. **6** and the corresponding discussion.

Besides changes in the drive signal frequency, the load impedance may also change. As previously described, load impedance changes may be induced by changing the number of ejectors fired in an AIP printing system. In order to compensate for changes in load impedance, a variable series impedance or "resonator" **516** is coupled in series with series impedance **412**. The impedance of reactive elements in the resonator are changed to compensate for load impedance changes.

In the illustrated embodiment, resonator **516** receives a load control signal along a load control line **520**. AIP printer circuitry (not shown) that drives the AIP printhead may be used to generate the load control signal. When used for AIP, the load control signal voltage is typically a function of the number of acoustic ink ejectors being fired at a particular point in time. For example, the load control signal voltage may be proportional to the number of acoustic ink ejectors being fired. By adjusting the impedance of variable reactive elements in resonator **516** to correspond to load impedance changes, an approximate impedance match can be maintained. One technique for implementing such a resonator will be illustrated in FIG. **6** and described in the accompanying description.

Different techniques, such as variable inductors and capacitors, may be used to implement variable reactance components. However, most variable components typically have a slow response time. AIP systems require a rapid response time because the number of ejectors fired typically changes within 300 nanoseconds, the time between ejector firings. Higher speed AIP printers may require even shorter times between firings. Thus, the impedance matching network needs to respond very quickly to rapid changes in load impedance as is well as frequency changes in RF output. One element that allows rapid changes in capacitance is a tuning diode. Such tuning diodes are commercially available from Motorola Corporation of Schaumburg, Ill. FIG. **6** illustrates a matching network **600** that uses tuning diodes to achieve a variable resonator and a variable shunt impedance. The described circuit is able to respond to changes in ejector firings on the order of 30 nanoseconds.

In FIG. **6**, a "transformer" or variable shunt impedance **504** is implemented using a pair of shunt tuning diodes **608**, **612**. Cathode **616** of shunt tuning diode **608** is coupled to cathode **620** of shunt tuning diode **612**. A frequency control signal is applied along frequency indicator line **512** to the cathodes **616**, **620** of each tuning diodes **608**, **612**. The frequency control signal includes a direct current (D.C.) offset voltage that keeps both tuning diodes **608**, **612** under constant reverse bias. The D.C. offset is typically about five volts when the tuning diodes are MV4001 tuning diodes from Motorola Corporation. A resistor **622** on frequency indicator line **512** controls current, although under most conditions, the constant reverse bias of tuning diodes **608**, **612** maintains a low current. A forward bias of tuning diodes **608**, **612** can result in high power dissipation that damages the tuning diodes.

A frequency indicator signal that indicates the frequency of the drive signal is superimposed on the D.C. offset voltage. The frequency control signal is the sum of the frequency indicator signal and the previously described D.C. offset voltage. When the drive signal linearly increases in frequency, the RF source generates a ramp signal voltage that linearly increases with the increasing frequency of the RF source. The ramp signal can be scaled and used as the frequency indicator signal. Plot **216** of FIG. **2** shows such a ramp signal that serves as a frequency indicator signal. As the voltage of the frequency indicator signal increases, the voltage of the frequency control signal that is applied to the tuning diodes also increases. The increase in the frequency control signal voltage increases the reverse bias on tuning diodes **612**, **608** of FIG. **6**. The increasing reverse bias decreases the capacitance of tuning diodes **608**, **612**. For example, in the previously described Motorola tuning diodes, as the reverse bias increases linearly from 5 volts to 6 volts, the capacitance decreases linearly from a maximum of approximately 30 picofarads at a 5 volts reverse bias to approximately 17 picofarads at a 6 volt reverse bias. Thus, as the drive signal increases in frequency, the capacitance of transformer **604** decreases to maintain an approximately constant shunt impedance.

FIG. **6** also illustrates a variable resonator **632** to adjust for changes in load impedance. Variable resonator **632** is implemented using two tuning diodes **636**, **640**. The cathode **648** of tuning diode **636** is coupled to cathode **652** of tuning diode **640**. Load control line **644** communicates a load control signal to cathodes **648**, **652**. The load control signal includes a DC bias that maintains reverse biasing of tuning diodes **636**, **640**. Current control resistor **656** further prevents excessive current from flowing through load control line **644**, although the reverse biasing of tuning diodes **636**, **640** will typically prevent excessive current.

As previously described, when used in an AIP system, the load control signal communicates information on the number of ejectors fired at a particular point in time. In one embodiment of the invention, circuitry within the AIP printer converts the number of ejectors to be fired into a voltage. The computed voltage is added to the DC offset to generate the load control signal that is applied to the cathodes of tuning diode **636**, **640**.

In some AIP print heads, the capacitance increases approximately linearly with an increase in the number of ejectors being fired. To compensate for the increased capacitance, the voltage of the load control signal is decreased. A decrease in the load control voltage decreases the reverse bias and thereby increases the combined capacitance of the tuning diodes **636**, **640**. When Motorola tuning diodes are used, a 6 volt reverse bias across a tuning diode may result in an approximately 17 pF capacitance. As the reverse bias voltage decreases, the capacitance of the tuning diode increases linearly with the decrease in bias voltage until the capacitance is approximately 30 pF at a reverse bias of 5 volts. The change in capacitance of tuning diodes **636**, **640** offsets inductances in first series impedance **408**, and second series impedance **412** to maintain an impedance match between source and load. In the illustrated example, the absolute value of the combined impedance that results from the sum of the inductance of second series impedance **412** and the capacitance of is variable resonator **632** is set equal to the absolute value of the impedance resulting from the capacitance of the load.

Changing the number of ejectors fired also changes the load resistance, the "real" part of the impedance. However, it has been found that changes in load resistance can be tolerated while still maintaining a reasonable standing wave ratio (SWR). In AIP systems, power losses resulting from impedance mismatches due to "real" part or resistance mismatches are small compared to the power losses that occur from impedance mismatches due to changes in the imaginary component of the impedance. Thus, in simple matching networks, compensation for the changes in the resistance may be unnecessary.

Plot line **212** of FIG. **2** illustrates the reflected power when the drive signal illustrated in plot line **204** is input into the matching network circuitry illustrated in FIG. **6**. The ramp signal plotted in plot line **216** of FIG. **2** was used as the frequency control signal. As can be seen, the matching condition is optimum at point **230**, however, at other frequencies, the standing wave ratio (SWR) remains reasonable.

While the invention has been described in terms of a number of specific embodiments, it will be evident to those skilled in the art that many alternatives, modifications, and variations are within the scope of the teachings contained therein. For example, the preceding specification has described using the matching network in an acoustic ink jet print system. However, other applications of the invention are also possible. Accordingly, the present invention should not be limited by the embodiments used to exemplify it, but rather should be considered to be within the spirit and scope of the following claims, and equivalents thereto, including all such alternative, modifications and variations.

What is claimed is:

1. A printer system including a dynamic impedance matching network for matching the impedance of a source of variable frequency oscillating energy to a printhead impedance of a printhead, the dynamic impedance matching network comprising:

a first reactive element to couple to a source of oscillating energy, the first reactive element including a first capacitance that changes as a function of the frequency of the received oscillating energy; and

a second reactive element coupled to the first reactive element, the second reactive element having a second capacitance that changes as a function of changes in the printhead impedance due to different firings of different ejectors in the printhead, such that an approximate impedance match is maintained between the source and the printhead.

2. The printer system including the dynamic impedance matching network of claim **1** wherein the reactive element includes at least one tuning diode.

3. The printer system including the dynamic impedance matching network of claim **2** wherein the reactive element includes a first tuning diode and a second tuning diode, a cathode of the first tuning diode coupled to a cathode of the second tuning diode.

4. The printer system including the dynamic impedance matching network of claim **3** wherein a voltage proportional to a frequency from the source of variable frequency oscillating energy is applied to the cathodes of the first tuning diode and the second tuning diode.

5. The printer system including the dynamic impedance matching network of claim **1** wherein the second reactive element includes at least one tuning diode.

6. The printer system including the dynamic impedance matching network of claim **1** wherein the second reactive element includes a first tuning diode and a second tuning diode, a cathode of the first tuning diode coupled to a cathode of the second tuning diode.

7. The printer system including the dynamic impedance matching network of claim **1** further comprising:

a series inductance coupled in series with the second reactive element, a combined impedance of the series inductance and the second reactive element set to resonate with a load impedance and create an impedance match.

8. A printer comprising:

a source of RF energy;

a printhead that includes a plurality of ink ejectors, the printhead having an impedance that corresponds to the number of ejectors ejecting ink; and

a matching network that couples the RF energy from the source to the printhead, the matching network having reactive elements that vary with the frequency of the RF energy and the number of ejectors ejecting ink such that an approximate impedance match is maintained despite changes in frequency of the RF energy and changes in the number of ejectors ejecting ink.

9. The printer of claim **8** wherein the frequency output by the RF source varies between 100 megahertz and 200 megahertz.

10. The printer of claim **8** wherein each ejector uses acoustic waves to eject ink.

11. The printer of claim **8** wherein the matching network comprises:

a transformer including a first reactive element to couple to the source of RF energy, the transformer to compensate for frequency changes in a signal output from the source; and

a resonator including a second reactive element coupled to the source of RF energy, the resonator to compensate for changes in load impedance due to changes in the number of ejectors being fired.

12. The printer of claim **8** wherein the matching network receives a signal from the source of RF energy, the voltage of the signal proportional to a frequency of a signal output from the source of RF energy.

13. The printer of claim **8** wherein the first reactive element includes at least one tuning diode.

14. A method of maintaining an impedance match between a RF source and load, the method comprising the operations of:

determining the frequency output from the RF source;

adjusting a first reactive element in an impedance matching network according to the frequency from the RF source;

determining the number of ink ejectors to be fired at a first point in time; and

adjusting a second reactive element in the impedance matching network according to the number of ink ejectors to be fired to maintain an impedance match between the RF source and the load.

15. The method of claim **14** wherein the adjusting of the first reactive element includes the operation of applying a voltage set by the output frequency for the RF source to a cathode of a tuning diode.

16. The method of claim **14** further comprising the operations of:

determining at a second point in time a second number of in ejectors to be fired; and

adjusting the second reactive element in the impedance matching network according to the number of ink ejectors to be fired at the second point in time to maintain an impedance match between the RF source and the load.

17. The method of claim **16** wherein the first point in time and the second point in time are less than 400 nanoseconds apart.

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